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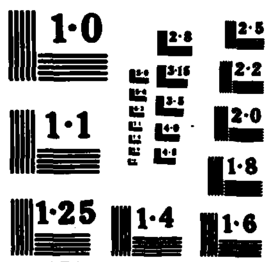
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DIFFUSION MODELING IN SUPPORT OF THE SPACE SHUTTLE

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The requirements for a computer model to forecast the diffusion of rocket exhaust during launches of the Space Shuttle are discussed. The model currently used, REEDM (Rocket Exhaust Effluent Diffusion Model), is described. Methods for dispersion, cloud-rise, gravitational deposition, and input data are discussed. Limited cases are explored which demonstrate both the value and limits of the REEDM.

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DIFFUSION MODELING IN SUPPORT OF THE SPACE SHUTTLE*

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ABSTRACT

The requirements for a computer model to forecast the diffusion of rocket exhaust during launches of the Space Shuttle are discussed. The model currently used, REEDM (Rocket Exhaust Effluent Diffusion Model), is described. Methods for dispersion, cloud-rise, gravitational deposition, and input data are discussed. Limited cases are explored which demonstrate both the value and limits of the REEDM.

BACKGROUND

The development of computerized atmospheric dispersion models for predicting the behavior of rocket engine exhaust clouds in the troposphere was initiated by Marshall Space Flight Center (MSFC) of the National Aeronautics and Space Administration (NASA) during the late 1960's. These models were needed to assist NASA in assessing the environmental impact of exhaust products from rocket engines with respect to air quality standards, toxicity thresholds and potential bio-ecological effects and in evaluating requirements, if any, for environmental launch constraints. In 1973, a joint program for rocket exhaust prediction and launch monitoring was initiated by NASA for all Titan launches from Kennedy Space Center (KSC). In this program, MSFC assumed responsibility for supplying dispersion-model predictions and Langley Researach Center made concentration measurements of rocket exhaust products at the surface and aloft through the use of aircraft sampling techniques with KSC providing the logistical support for these activities. This program revealed the need for the development of real-time dispersion prediction capability and the measurements made during the program provided a data base which could be used in verifying the accuracy of model predictions and in making model improvements. This work lead to the development of the REEDM, which is used to assess the environmental impact of Space Shuttle operations and to provide a real-time dispersion prediction capability during launches of the Space Shuttle at the Eastern Test Range (ETR).

GENERAL DESCRIPTION

The REEDM computer code includes basic mathematical expressions for atmospheric dispersion models, cloud-rise models and models for calculating the gravitational deposition of acid drops. Inputs are vehicle and other source parameters, meteorological parameters defining the state of the planetary boundary layer (including turbulence parameters) and physical properties of the rocket exhaust cloud. During launches of the Space Shuttle, the rocket engines emit large quantities of exhaust products, which combine with water from the sound suppression system and result in the formation of a large hot acid cloud near ground level. The cloud grows rapidly through entrainment and, shortly after ignition, it lifts off the ground and rises to its stabilization height. Typically the top of the stabilized cloud produced by the Space Shuttle is more than 2 kilometers above ground level (AGL). By convention, this cloud is referred to as the ground cloud. The rocket engines of the ascending vehicle also leave an exhaust trail which extends through the troposphere and beyond. The REEDM computer program is designed to calculate peak concentration, dosage and surface deposition (resulting from both gravitational settling and precipitation scavenging) of ground cloud constituents downwind from normal launches and launch failures. The current meteorological inputs to REEDM are the vertical profiles of wind direction, wind speed, air temperature, atmospheric pressure and dew point or relative humidity in the lower 3,048 meters (10,000 feet). It is possible to incorporate additional information about the current state of the planetary boundary layer which may be obtained from towers, remote sensing instruments or surface measurement stations. It is also possible to replace any or all meteorological input data with forecast values.

*A part of this work was under Contract No. F08606-83-C-0014 with ESMC, Patrick AFB, FL.

PROGRAM COMPONENTS

The REEDM program currently used at the ETR is divided as illustrated in Fig. 1. The five major parts are: meteorological inputs, source inputs dependent on launch vehicle and type of launch, cloud-rise and material distribution algorithms, the dispersion model algorithms (there are three--dosage/concentration, gravitational deposition and washout deposition) and output routines.

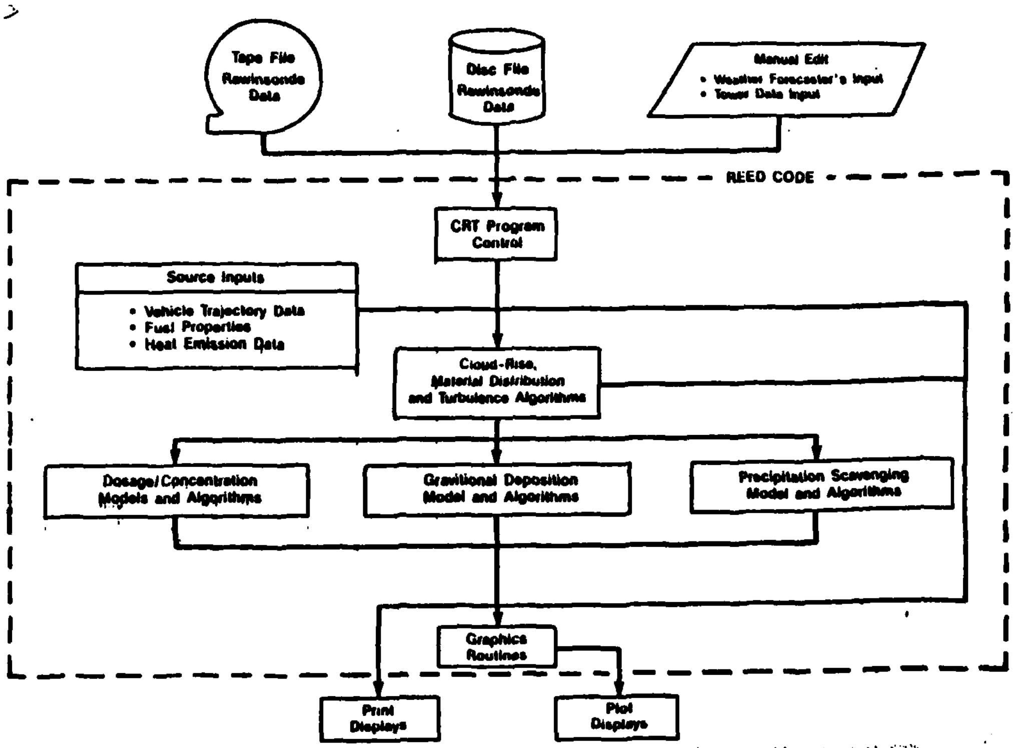

Figure 1. Schematic diagram of the major components of the REEDM program.

METEOROLOGICAL INPUTS

The program meteorological inputs all come from disk files resident on the same computer system as the program. During launch support, the meteorological data are updated by other support programs and/or replaced with forecast values. Although it is desirable to use all the sources of meteorological data, the REEDM program has been developed to execute with the rawinsonde as minimum input. Additionally, a model has been added to support Shuttle launches at the Western Test Range (WTR) which incorporates the influence of the complex terrain found there. The wind field model is based on the shallow water equations of oceanography and has been shown, under certain conditions, to calculate accurate wind field patterns in complex terrain. These conditions arise when the atmosphere above the terrain can be divided into two or more layers of different density. The usual condition prevailing at the WTR of a cool marine layer capped by a warmer, dry layer generally fits this model. The wind field in the region of interest is obtained by using a constant velocity throughout the lower layer, obtained from a suitable average of the wind speed in the mixing layer as measured by rawinsondes. After 3 to 4 hours of model time, the modelled transient waves decay or move out of the region and the resulting solution describes the steady state wind field. Trajectories of air motion through the wind field define a curvilinear coordinate system for dispersion model calculations.

SOURCE INPUTS

Source inputs are selected from stored values according to the type of launch vehicle and launch conditions. These consist of flight trajectory data, heat emission data and exhaust chemical constituents. These data affect the cloud rise calculations and total quantity of each reaction product used as input to the dispersion models.

CLOUD RISE AND MATERIAL DISTRIBUTION ALGORITHMS

Cloud Rise. The cloud rise algorithms are based on the work of Briggs (1969). For normal launches his instantaneous cloud rise model is used. This model assumes that entrained air increases the radius of the ascending cloud as a linear function of height gained after cloud formation. The REEDM program is a multi-layer model with the layer boundaries defined by the rawinsonde reporting levels input. To reduce error which occurs with excessively thick layers, the program interpolates intermediate levels as needed. During incorporation of the acid drop deposition algorithm into REEDM, it was found that limitations also had to be placed on the amount of directional shear within a layer. Once a satisfactory layering has been determined by the program, the cloud rise algorithm computes the height and vertical velocity of the cloud centroid as a function of time and output values at each layer boundary below the cloud stabilization height. The calculation of cloud vertical velocity is done on a layer-by-layer basis with the value of the stability parameter used in the cloud rise algorithm for each layer being computed from the average of the stability parameter through the vertical extent of the cloud (from the bottom of the cloud through the top of the cloud). The heat available for cloud rise through a layer requires vehicle flight profile data, stored in the program and derived from a power-law expression. The heat available is then the total heat output of the launch vehicle from engine ignition until the time the launch vehicle passes through the layer. The heat output has already been adjusted for the effects of radiation, after-burning, and vaporization of the deluge water. In the launch failure mode, a continuous source model is used. Among other factors, the continuous cloud rise model assumes less ambient air is entrained in the rising plume.

Acid Drop Deposition. In the acid drop deposition model, the vertical velocity used to carry the drops up into the cloud is computed assuming that there exists a parabolic velocity profile with a mean vertical velocity equal to the cloud rise velocity in each layer. The height to which drops are carried is computed by integrating the drop net velocity (local cloud vertical velocity minus the settling velocity for each drop size category) for as long as the net velocity is upward. This integration is performed for points at the center of the cloud and at the edge, and defines the range of heights reached by each drop size category. Drops are assumed to fall clear of the cloud when their net velocity becomes negative. Drops falling out in each layer are assigned to that layer as the source for the deposition model. Since the deposition model output depends on the assumed drop size distribution and the only drop size distributions available were measured within the cloud at heights of 700 meters (Fig. 2), the initial (ground level) distribution was computed by using the cloud rise model and the drop source algorithm to match the distribution at the measured height of 700 meters. The derivation of the initial drop size distribution assumes that no evaporation takes place as long as the drops remain within the ascending ground cloud. However, evaporation of the water component is modeled during the fall back to earth.

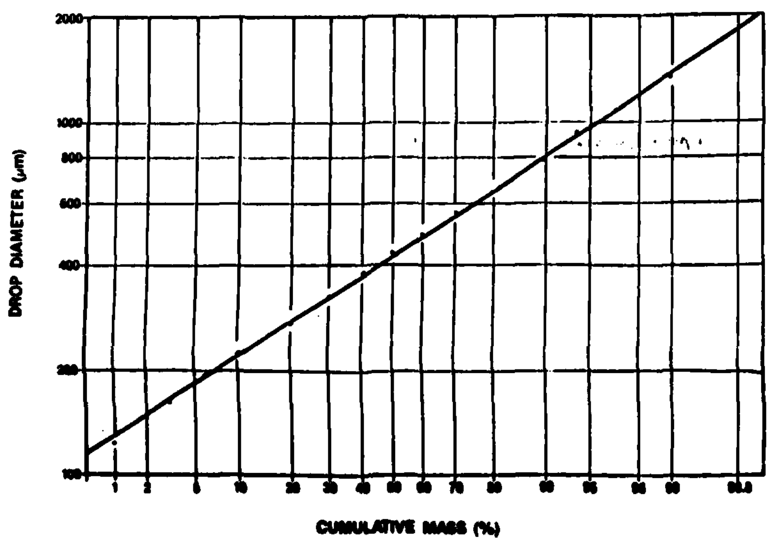

Figure 2. Cumulative mass distribution of acid drops based on the number distribution measured at an altitude of 700 meters during STS-3 (solid line) and mass distribution predicted by the model at 700 meters (dots).

The effect of HCl concentration on the partial pressure of water vapor over the solution drop has been described by a set of empirical equations (Dingle, 1978) using curve fitting techniques to define coefficients as a function of molality in the equations. In the current version the complex interaction of the vapor pressure of water over an HCl solution drop of variable molality is simplified by using mean values of the coefficients for a molality of 2. The evaporation algorithm uses the Frossling equation to compute the time rate of change of droplet radius.

Dispersion Models. The dispersion models used in the REEDM code are based on Gaussian model concepts which experience has shown to be best suited for most practical applications. A detailed discussion of Gaussian modeling concepts and alternative approaches is found in Pasquill (1975) and Gifford (1975). As pointed out in Dumbauld and Bjorklund (1975), the Gaussian approach, when properly used, "---is peerless as a practical diffusion modeling tool. It is mathematically simple and flexible, it is in accord with much though not all of working diffusion theory, and it provides a reliable framework for the correlation of field diffusion trials as well as the results of both mathematical and physical diffusion modeling studies." In the REEDM dispersion model code, the exhaust material is assumed to be uniformly distributed in the vertical and to have a bivariate Gaussian distribution in the horizontal plane at the point of cloud stabilization. It follows from these assumptions that the models are of the general form identified with Gaussian models for vertical line sources of finite extent.

MODEL RESULTS

In general, the REEDM shows reasonable estimates of concentration, dose, and deposition provided the meteorological conditions input to the model are realistic. However, there exist certain difficulties when the program is run prior to launch with changing meteorological conditions. Winds shifts, temperature profiles (especially inversions) and turbulence changes are very significant. Changes in moisture play a lesser role. A sample case was the launch scheduled for 4:30PM EDT 12 July 1985. Figure 3 shows the surface weather map for 0800 EDT 12 July 1985 and Fig. 4, the upper level flow at 500 millibars. With no synoptic features to consider, forecast of the seabreeze represented the largest forecast problem. Figure 5 (Case 1) represents REEDM output for time of launch (4:30PM EDT) using winds actually measured at 11:30AM EDT. Figure 6 (Case 2) represents REEDM output with input data modified below 975 meters to account for the seabreeze (persistence was assumed above 975 meters). By 2:00PM EDT (Case 3), not only had the seabreeze began, but winds from the southeast extended throughout the 3048 meters modelled. By 3:30PM EDT (Case 4), winds continued from the southeast and generally strengthened throughout the modelled layer. Figures 7 and 8 depict REEDM meteorological output for these two cases. Tables 1 and 2 show selected levels of winds input to the model for these two cases. Table 3 lists selected intervals of ground level deposition along the center line of diffusion for Case 2.

SUMMARY

Given the current model, the primary requirement to obtain valid output from the REEDM is quality meteorological input data. Those data are currently input by forecasting via editing of meteorological data files available at the ETR complex from rawinsondes released prior to launch and modified as required. Recent Shuttle launches indicate acceptable operational results, provided reasonably correct forecast data are input to the model.

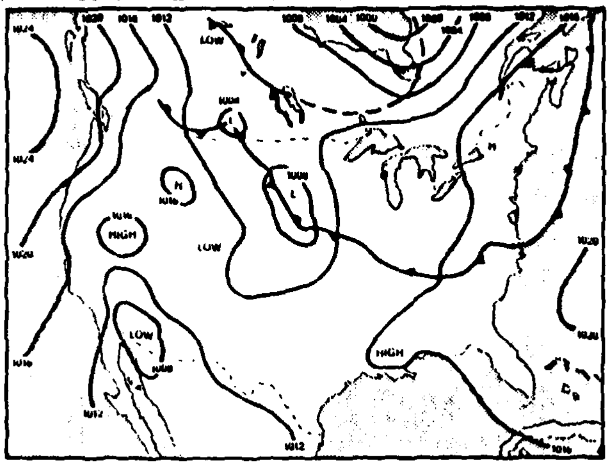

Figure 3. SURFACE WEATHER MAP at 1200 GMT 12 Jul 85.

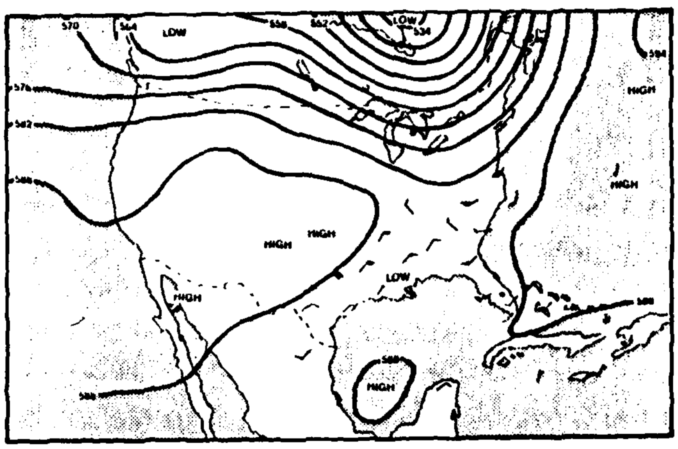

Figure 4. 500-MILLIBAR HEIGHT CONTOURS at 1200 GMT 12 Jul 85.

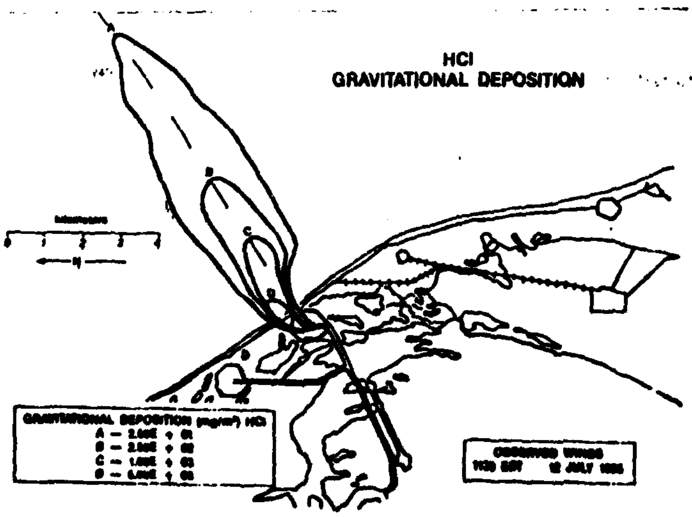

Figure 5. HCl gravitational deposition as modeled by REEDM using rawinsonde input data observed at 1130 EDT on 12 July 1985 (Case 1).

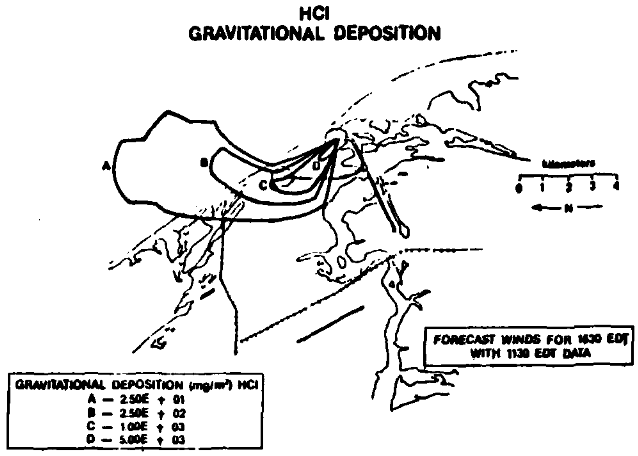

Figure 6. HCl gravitational deposition as output by REEDM using forecast data for 1630 EDT based on 1130 EDT information (Case 2).

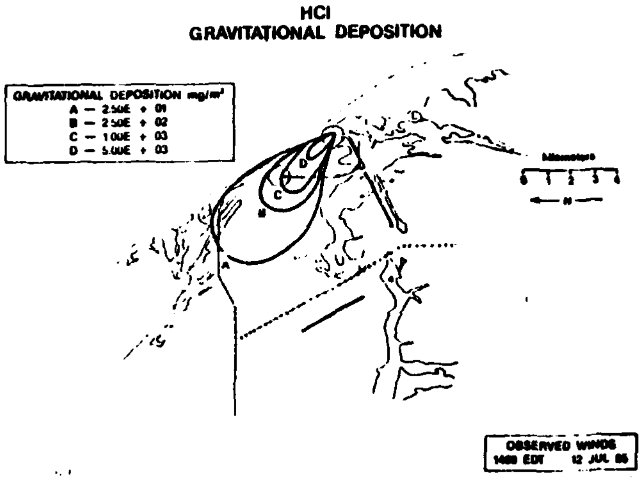

Figure 7. REEDM HCl gravitational deposition using the 12 July 1400 EDT rawinsonde data (Case 3).

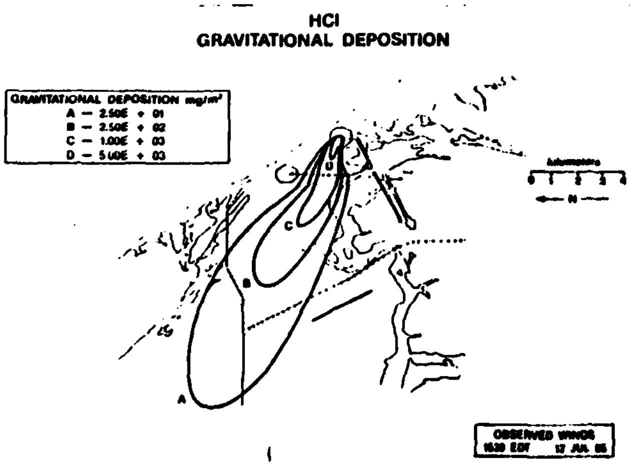

Figure 8. HCl gravitational deposition modeled by REEDM using the 1530 EDT rawinsonde data (Case 4).

LEVEL	ALTITUDE (FT)	ALTITUDE (M)	DIR (DEG)	SPEED (M/S)	SPEED (KNOTS)	TEMP (^{o}C)
1	16	5	100	5.1	10	31.6
8	543	166	105	5.1	10	29.3
10	1,000	305	120	4.1	8	27.4
13	2,000	610	150	2.6	5	23.8
16	3,000	914	180	2.6	5	22.8
20	3,200	975	220	2.6	5	22.3
24	5,000	1,524	235	1.5	3	18.6
35	10,000	3,048	235	2.1	4	8.5

Table 1. Selected Levels of Meteorological Input Data for Case 2.

LEVEL	ALTITUDE (FT)	ALTITUDE (M)	DIR (DEG)	SPEED (M/S)	SPEED (KNOTS)	TEMP (^{o}C)
1	16	5	100	4.6	9	30.3
8	497	152	98	4.6	9	28.3
11	1,000	305	96	4.6	9	26.1
16	3,000	914	124	3.1	6	22.9
19	4,000	1,219	132	2.6	5	20.6
24	6,000	1,829	131	2.1	4	16.0
29	8,000	2,438	130	1.0	2	11.9
33	10,000	3,048	117	0.5	1	7.9

Table 2. Selected Levels of Meteorological Input Data for Case 4.

RANGE (METERS)	BEARING (DEGREES)	HCl DEPOSITION (MG/M^2)
400	310	10,942
1,400	307	3,389
2,400	308	1,600
3,600	331	843
4,400	347	190
8,400	351	37
12,400	352	5.1
16,400	352	1.4
20,400	352	0.4
24,400	348	0.14

Table 3. Gravitational Deposition for Case 2.

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